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Seawater Intrusion at Abandoned Coal Mines in the Labin Region, Croatia

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Abstract

Underground coal mines in the Labin Paleogene basin on the Istrian peninsula in Croatia ceased operation in 1988 after more than two centuries of mining. Throughout the next three years, most of the mines were flooded. The total volume of exploitation fields and stable underground corridors that had been flooded by groundwater was estimated at 12 million cubic metres. Given that the mine works had drained the surrounding karst aquifer, it was assumed that stored waters and underground recharge could be used for public water supply or for industrial purposes. To confirm this assumption, comprehensive hydrogeological research was conducted, including quantifying the geometry and volume of flooded underground works, identifying hydrogeological characteristics of the rock units, and exploring the water hydrochemistry and dynamics. Ultimately, despite favourable hydrogeological conditions and large drainage capacity, it was determined that the hydrochemical characteristics of the mine waters rendered the water unsuitable for most uses. One of the highlighted problems was the excessive chloride content. Since the mines are located in permeable carbonate rocks and their deepest parts are only 1 km from the coastline, seawater intrusion was a common occurrence at the time of exploitation. Data from this period show that the drainage water in the deepest parts of the mine consisted of 25 to 85% seawater.

Although several available shafts have been investigated, the results obtained in the Labin shaft are representative of the entire mining system due to its drainage function and intensive groundwater dynamics. During low water conditions at the top of the water column (up to a depth of 60–70 m), fresh water with a chloride content of <250 mg/L prevails. The chloride content significantly increases with depth. At a depth of –200 m, it ranges from 1,350 to 2,010 mg/L, while at the bottom of the shaft at a depth of –350 m, the content ranges between 1,810 and 2,380 mg/L. During high water conditions, overflow from the shaft appears. The content of chlorides in the overflow water ranges from 194 up to 1,200 mg/L.

Introduction

The very first data about mining in the area of the Labin Paleogene basin on the east side of the Istrian Peninsula date back to the year 1420, and the data are about the extraction of coal and resin surface outcrops. Underground coal mining started in 1755. Until 1924, all excavations were conducted above the groundwater table in several so-called "old pits". Investigations have shown that the thickest coal layers are located on the eastern edge of the syncline structure and, following the bedding, gradually sink to greater depths. Because of this finding, three new pits (shaft mines) were opened: Raša, Labin, and Ripenda, in which coal was extracted from below groundwater levels. The pits are well interconnected at several levels. Following the spread of the coal layers, pits were developed from the southwest towards the northeast, and in this direction, the depth of mining increased. Thus, Raša mining was conducted up to approximately 300 m in depth, Labin mining was up to 400 m, and Ripenda mining was conducted at up to almost 500 m in depth.

The golden age of mining began just before World War II. A record production of 1.2 million tons was achieved in 1942, when mining in the "new pits" had already reached a depth of –250 m below sea level. Despite strong financial support from the former Yugoslavian government, the next decades were marked by a gradual decline in production, followed by a large increase in the operational costs of mining and drainage in works that reached depths of approximately –500 m below sea level. After the cessation of mining activity in 1988, large parts of the abandoned underground works were flooded.

The total volume of exploitation fields and stable underground corridors flooded by groundwater was estimated at 12 million cubic metres (Kuhta, 2004). Given that the mining works had drained the surrounding karst aquifer, it was assumed that stored waters and underground recharge could be used for public water supply or for industrial purposes. To confirm this assumption, comprehensive hydrogeological research has been initiated, including quantifying the geometry and volume of flooded underground works, identifying the hydrogeological characteristics of the rock units, as well as exploring the water hydrochemistry and dynamics. Ultimately however, despite the favourable hydrogeological conditions and large drainage capacity, it was determined that the hydrochemical characteristics of the mine waters limit their potential uses. One of the highlighted problems was the excessive chloride content. Since the coal mines are located near the sea, some parts are less than 1 km from the coast, and the extraction in the karst environment occurred well below sea level; salt water intrusions were a common occurrence during the exploitation. It was assumed that the seawater intrusions would stop after the mines were flooded with fresh groundwater. However, even during the first investigations (Rubinić et al., 1993, 1995), was shown that the chloride content in the groundwater exceeded the Maximum Allowable Concentration (MAC) for drinking water. Since this could significantly reduce the utility of these waters, the chloride content has been specifically studied during this project.

Study Area

The site being investigated is located in the Dinaric karst area that covers the southern half of Croatia (Figure 1). Coal mines in the Labin area are formed within the Istrian Tertiary syncline, which stretches across the northern part of the peninsula for about 90 km. Although coal deposits occur in other parts of the syncline, exploitable quantities were determined only in the area of Labin and the nearby Pićan basin. The geology of the Labin area, as well as the position of the mines, is shown in Figure 1.

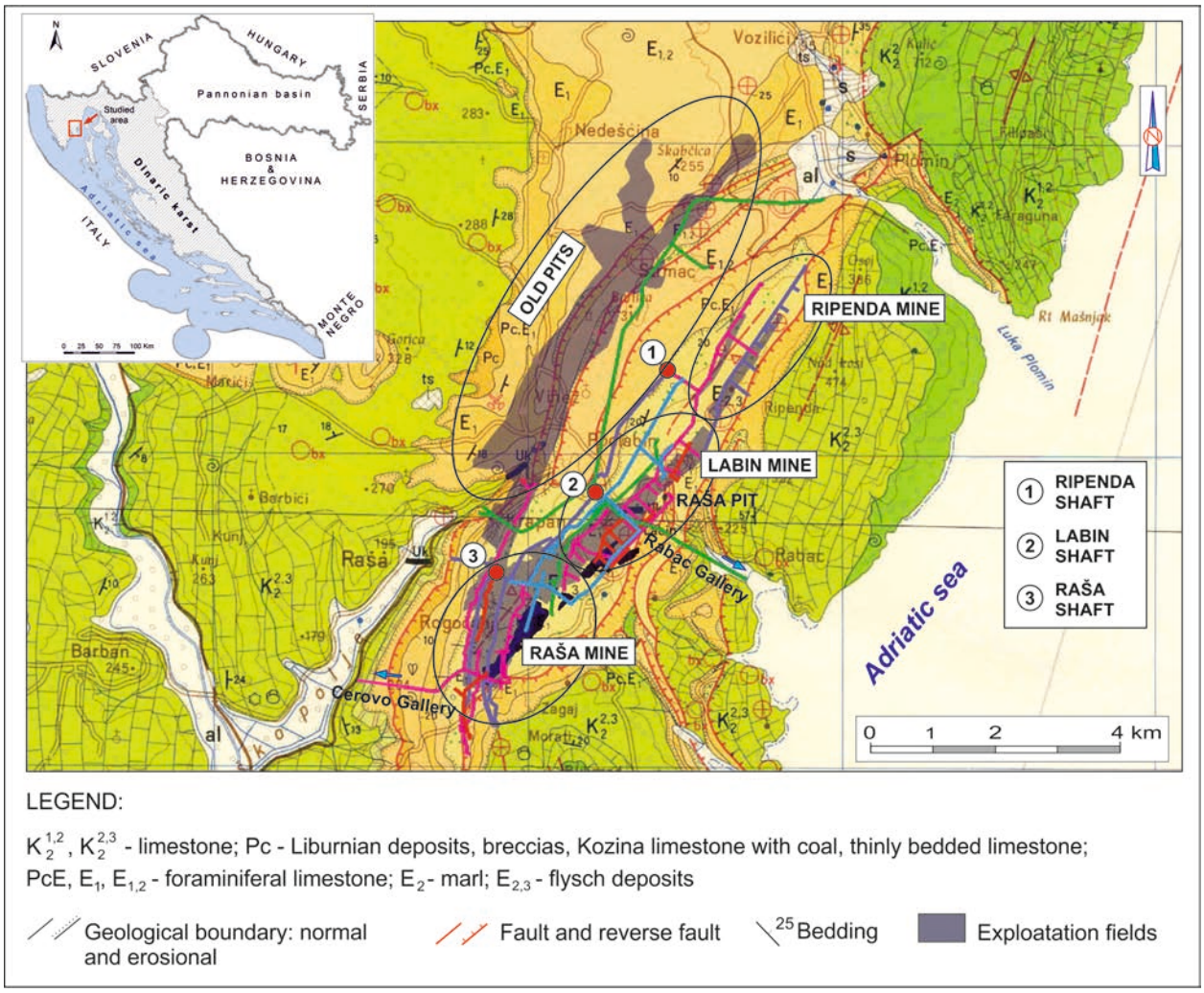

Figure 1: Geological map of the Labin coal mines area (geology after: Šikić et al., 1969)

The basement of the coal layers is made up of carbonate deposits of the Upper Cretaceous, predominantly represented by different types of limestone (Šikić et al., 1969; Šikić and Polšak, 1973). Deposition during the Paleogene was mainly controlled by intense syn-sedimentary tectonic deformation of the former carbonate platform area. After the emersion period during the transition between the Cretaceous and the Tertiary periods, the first Paleogene sediments were deposited within several isolated

fresh water basins on the karstified Cretaceous basement. The first lithostratigraphic unit was Liburnian deposits of Paleocene (Pc). The series begins with breccias, on which (or directly on Cretaceous deposits) follow the so-called Kozina limestone, which is brown to dark grey, dense and homogeneous, predominantly bituminous limestone with varied freshwater and brackish fauna and flora. Within this limestone, there are numerous layers of coal, ranging from several centimetres to over 3 m thick. This coal falls into the category of bituminous coal, with a heat content of 25–31 MJ/kg, and is characterized by its high (8–10%) sulphur content of organic origin. In the upper part of the Liburnian sediments, there is thinly bedded light to dark grey limestone, which comprises the transition to the upcoming marine sedimentation conditions. The total thickness of the Liburnian deposits is from 100 to 150 m, and the thickness of the Kozina layers with coal ranges from 80 to 120 m.

The conditions of carbonate sedimentation continued through the Upper Paleocene and lasted until the Middle Eocene. During this period, 100 to 180 m thick foraminiferal limestone series (Pc,E) were deposited. After the deposition of foraminiferal limestone, the orogenic deepening of the sedimentation environment occurred, and deposition of clastic deposits gradually prevailed. First, the marls of the Middle Eocene (E_2) were deposited, followed by deposition of flysch deposits ($E_{2,3}$), which also consist mainly of marls but frequently change to various types of limestone, sand, breccia and conglomerate.

Thereafter, due to the strong north-east-south-west-oriented regional tectonic stress, thrust-related deformations occurred, reaching a maximum in the Oligocene/Miocene, when the complex tectonic structure of the Dinaric region was formed (Korbar, 2009). The Istrian Tertiary syncline was uplifted, and its northeast wing was reversely faulted and thrusted, resulting in its modern shape.

Large areas of carbonate rocks, formed by intensive tectonic disturbance and dynamic endogen processes, result in very deep and irregular karstification and complex hydrogeology. The vast thickness of the carbonate deposits allows for the development of deep karst aquifers. In such circumstances, any mining below the groundwater table results in the activation of lateral inflows. Given the great mining depth and the long duration of exploitation, i.e., the intensive drainage of groundwater, it can be assumed that a wide depression cone was formed around the mains; this cone influenced the hydrogeology of the wider area. Furthermore, the proximity of the karst aquifer to the sea allowed salt water intrusions. This phenomenon was particularly pronounced in the development works on the eastern side of the mines.

With the cessation of mining and the flooding of the open underground spaces, the process of restoring natural hydrogeological norms followed, but this process will not be completely realized. First, there are numerous artificial underground channels in the aquifer that connect parts of the system that, in natural conditions, would likely be separate. In addition, the drainage galleries Rabac (connected to the Labin shaft; 10.53 masl; Figure 1) and Cerovo (connected to the Raša shaft; 10.81 masl; Figure 1) drain

the aquifer during the high-water states, which changes the natural discharge conditions and reduces aquifer storage.

Methodology

To show the concentration and dynamics of the chloride content in the mine's drainage waters at the time of coal extraction, privately archived data from mine geologist Mr. Mirko Tomašić were used. The amount of chloride in the groundwater at the Labin shaft and in the drainage gallery of Rabac in the period soon after flooding, i.e., from 1992 to 1994, was processed on the basis of data from Rubinić et al. (1993, 1995). The majority of the data was collected during a hydrogeological investigation conducted by the Croatian Geological Survey, 2003 (Kuhta, 2004). During these explorations, the groundwater of the entire mining system was examined. The major observation points were the main shafts Labin, Raša, and Ripenda. The results obtained are quite similar; as a representative, the situation on the Labin shaft is described. The Labin shaft is 573 m deep (Figure 5). Its entrance is at an altitude of 218 masl, but is currently closed with a concrete plate. The only possible access to the shaft today leads through a 2.6 km long drainage gallery from Rabac. The gallery is connected to the shaft at the altitude of 10.53 masl. The submerged part of the shaft is approximately 360 m deep (depending on the groundwater level). In the sunken section, a few mining horizons (levels) are connected to the shaft at the depths of –140, –242, –303 and –352 metres. Through the first three horizons, direct communication is possible with the Labin mine, as well as with the Raša and Ripenda mines. Direct communication is not possible through the lowest horizon, since the water gate on that horizon was closed before the flooding.

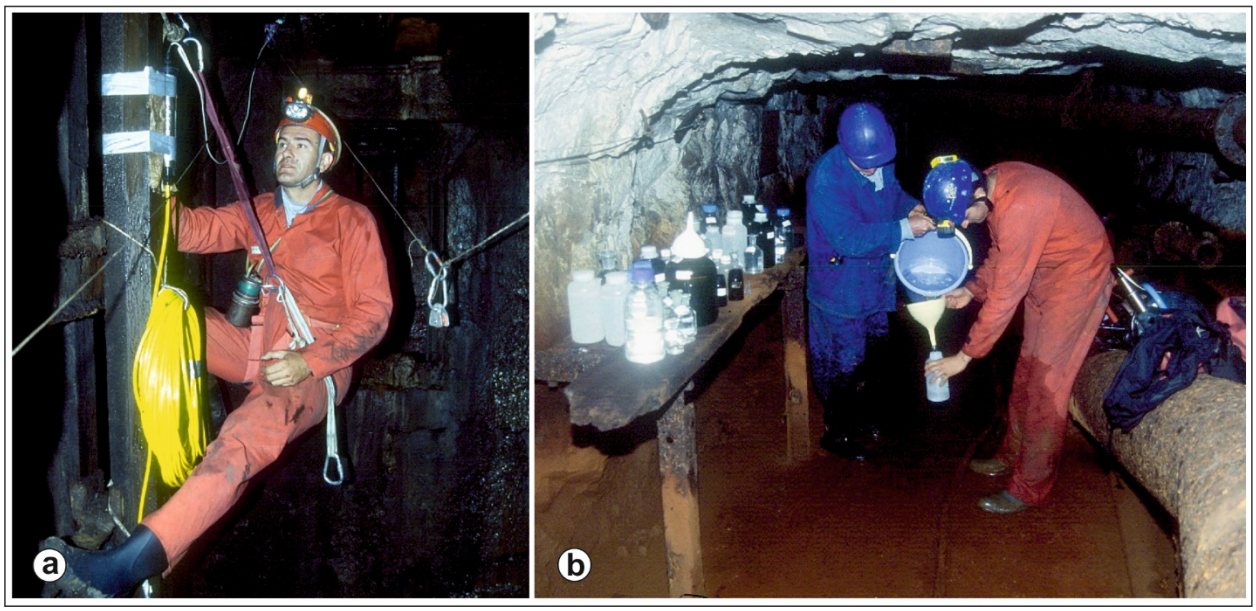

Figure 2: Groundwater level logger (a) and sampling in the Labin shaft (b)

The groundwater level in the shaft was measured every 6 hours using a WL 15 (Global Water, USA) logger (Figure 2a) from April 2003 to January 2004. The operation of the device was calibrated periodically with manual measurements taken with a Water Level Meter. Data on the daily precipitation in the Labin area were obtained from the State Meteorological and Hydrological Service.

Groundwater samples (Figure 2b) were collected using a bailer every 50 m to a depth of –340 m. This sampling was carried out on four occasions, during various hydrological conditions. At the same time, field measurements of water temperature and electrolytic conductivity were performed using KLL-MPS-D3 multiparameter probes (SEBA Hydrometrie, Germany). The measurements were performed every 10 m to a depth of –190 m. Chemical analyses of the samples, including the chloride content (Cl–), were performed in the laboratory of the Public Health Institute of the Istrian County in Pula.

Results

The content of chlorides in mining groundwater varies depending on the hydrological conditions in the wider area. The groundwater dynamics were processed on the basis of the groundwater level (GWL) measurements from the Labin shaft.

Groundwater Dynamics

The Labin shaft has a very important role in the groundwater dynamics within the study area. At an altitude of 10.53 masl, the shaft is connected to the 2.6 km-long Rabac gallery that ends at the seashore. In low water conditions, the GWL is below the height of the overflow (Figure 3). In high water conditions, i.e., when GWL reaches a 10.53 masl, the groundwater drains directly into the sea through the Rabac gallery. It should be noted that the Rabac gallery is directly connected to the "old pits", which are situated over the groundwater table, and therefore, the gallery drains percolating waters from that area as well.

The daily precipitation recorded by the Labin weather station and the results of the GWL measurements are highly correlated (Figure 3). The reaction of the GWL to precipitation is very fast and confirms the highly karstic characteristics of the aquifer. The lowest GWL of 6.85 masl on the Labin shaft was reached at the end of the dry season at the end of September 2003. The extreme amount of precipitation that fell on the 29th of September 2003 caused a sudden rise in groundwater levels of almost 4 m, and the discharge was activated. The overflow practically did not stop until the end of the observation period. The highest levels of groundwater were recorded after heavy precipitation on 31st December, 2003, when a total of 97 mm of rain fell. On the same day, the groundwater level reached 11.38 masl. The difference between the minimum and maximum recorded GWL was only 4.53 m. According to Rubinić et al. (1995), the highest recorded GWL in the observation period from 1992 to

1994 was 13 masl. It can be assumed that it would have been significantly higher if there were no drainage possibility through the Rabac gallery and Cerovo gallery on the other side of the system.

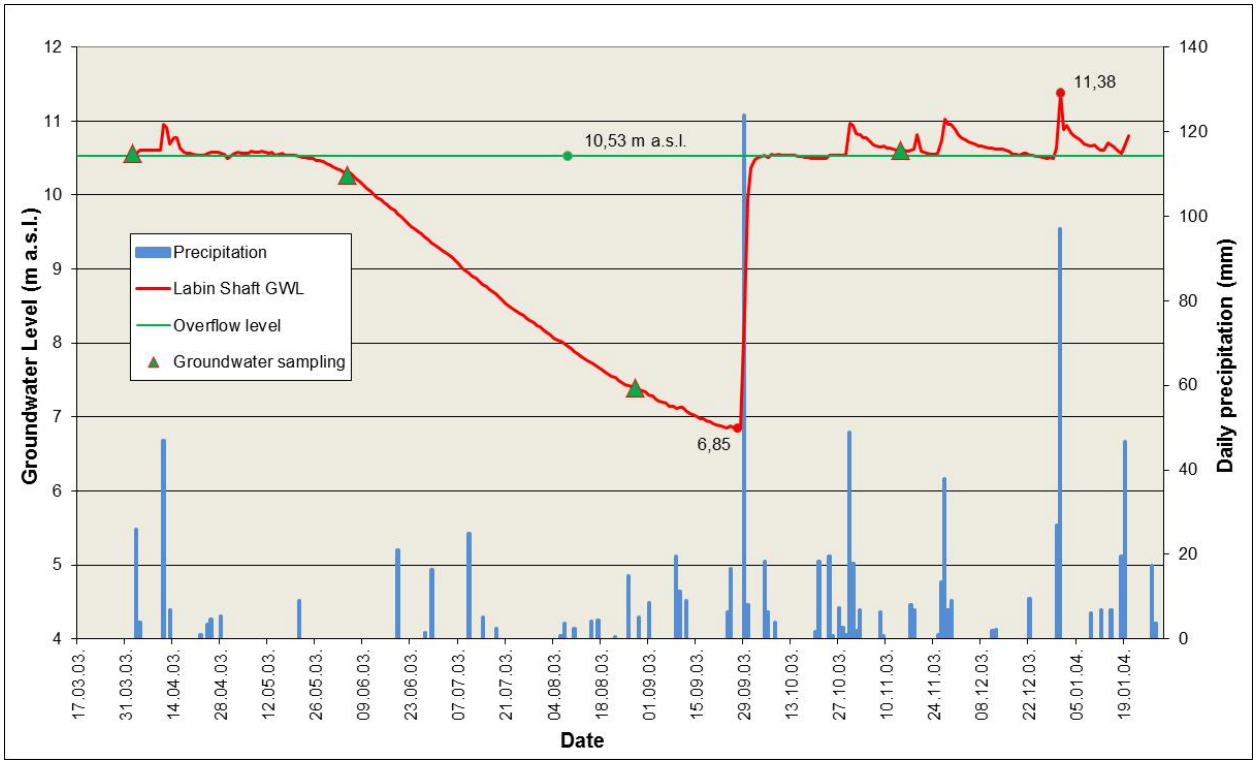

Figure 3: Groundwater level (GWL) on the Labin shaft compared with daily precipitation

During dry periods, there is no outflow at the exit of the Rabac gallery. At higher water conditions, it usually ranges from tens to several hundreds of L/s (Figure 4a). However, in extreme situations the discharge can reach over 10 m^3/s (Figure 4b).

Figure 4: Discharge on the exit of the Rabac drainage gallery during "normal" high water conditions (a) and in an extreme situation on October 1993 (b)

Chloride Content Variations

During the extraction period, smaller or larger amounts of seawater were regularly recorded on the eastern outermost corridors, from the Raša mine through Labin to Ripende. In 1934, an accidental breakthrough of seawater occurred on the XIV horizon (–140 m) in the southern part of the Raša mine ("Cavern" area), which was a particularly serious problem. Most of the mine was first flooded with fresh groundwater and mud, which was followed by an intrusion of clear seawater. The area was closed and isolated, but further coal extraction was abandoned in that part of the mine.

With the exception of this event, it can generally be concluded that the amount of seawater has increased with exploitation depth, that is, from the south towards the north. The most prominent occurrences of seawater were recorded at the XIV (–140 m) level in the Raša mine, the XX (– 340 m) and XXIV (–450 m) levels in the Labin mine, as well as at the XXIV and XXV (–440 and –480 m) levels in the Ripenda mine. The content of chloride in the drainage waters of Ripenda was reconstructed on the basis of data collected during 1984/85 (private archive data of Mr. Tomašić). Observation points were located in the deepest corridors (–450 to –480 m), which are from 850 to 1,350 m away from the seashore. The total chloride content was very high. In the more heavily loaded sectors, it usually ranged from 6,000 to 12,000 mg/L, which means that the percentage of seawater in the drainage was between 25 and 50%. At maximum salinity (approximately 16,000 mg/L Cl), it reached 70%. The variations in chloride content were very poorly correlated with the levels of precipitation.

The impact of seawater intrusions was observed during the first research efforts immediately after the flooding of the mines (Rubinić et al., 1993, 1995). The results of sampling carried out along the depth of the water column in the Labin shaft showed that during low water conditions and in the shallow depths, the chloride content was approximately 100 mg/L, but at greater depths, they were significantly higher. For example, at a depth of –140 m, they reached up to 1,000 mg/L, and at a depth of –350 m, they reached above 3,000 mg/L. In periods of high groundwater, samples were taken at the exit of the Rabac gallery. According to the results, the chloride content was also high in these cases and frequently ranged from 300 to 600 mg/L, with a maximum recorded value of 1,200 mg/L. It is important to recall that in such conditions, the drainage water of the Rabac gallery also contains an unknown quantity of fresh water that has drained in from the "old pits" situated above the groundwater table.

The salinity measurement of the main waters during investigations from 2003–2004 was carried out during four field tours that aimed to capture different hydrological conditions (Figure 3). The temperature, electrolytic conductivity and chloride concentration data in relation to the location in the water column within the Labin shaft are shown in Figure 5.

The measurements indicate that in low water periods (no overflow from the shaft), the surface layer of fresh water reached depths of about 60–70 m. Below this depth, chloride content was found to be

constantly higher than the MAC for drinking water (250 mg Cl^-/L), and was found to increase with depth. The most significant changes occurred at depths below –140 m, i.e., after the connection of the XIV level to the shaft. At a depth of –140 m, chloride content ranged from 380–550 mg/L. The changes were particularly pronounced between –180 and –190 m, where the XVI level is connected. At this point, the chloride content rapidly increased, and ranged from 1,350 to 2,010 mg/L. Chloride content continued to increase as depth increased, but these changes were not as pronounced. At –240 m, the chloride content ranged from 1,470 to 2,210 mg/L, and near the bottom of the shaft, at –340 m, it ranged from 1,810 to 2,380 mg/L. Chloride content changes in the area of the XIV and XVI levels were followed by a sudden rise in water temperature.

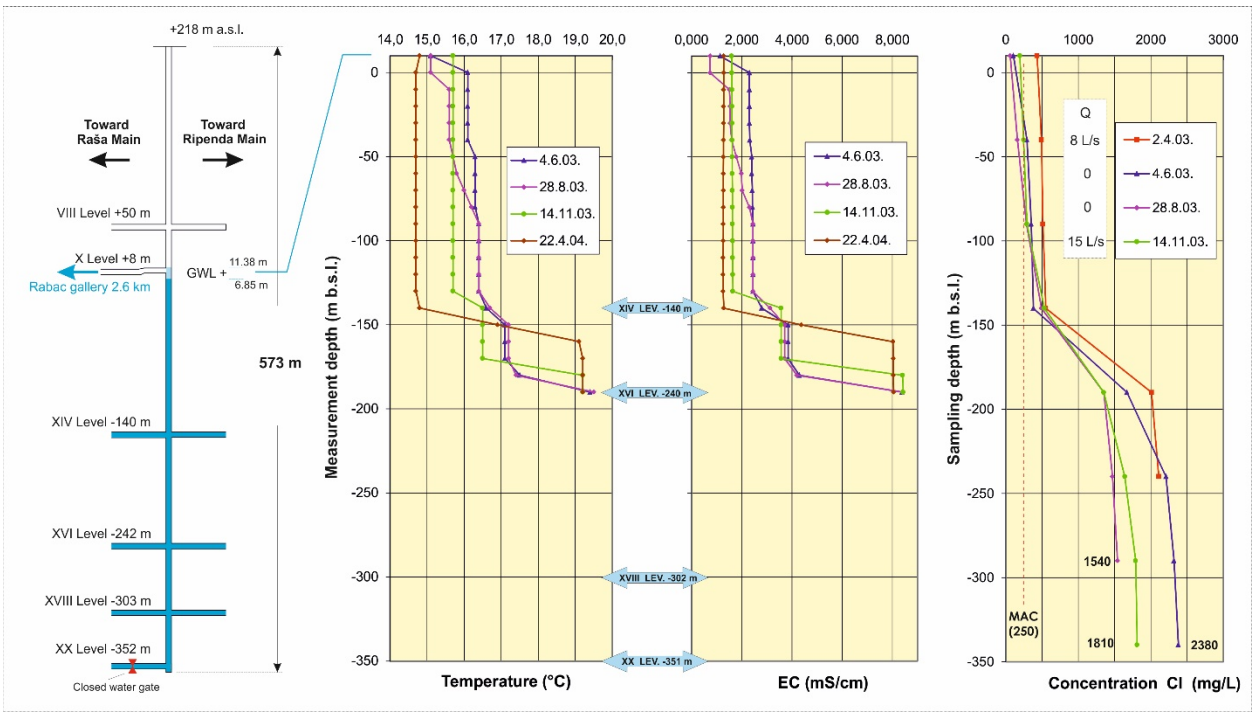

Figure 5: Water temperature, EC and Cl^- concentration in Labin shaft

During high water periods, i.e., instances of outflow from the shaft to the Rabac drainage gallery, the chloride content was determined on two occasions (Figure 3). At the time of the first sampling (2nd April 2003), the chloride content was 430 mg/L. Sampling was carried out immediately after the start of outflow (approximately 8 L/s). The second sampling (14th November 2003) was performed after a longer outflow period (approximately 15 L/s), and the chloride content was significantly less (only 194 mg/L).

Discussion

During the full development of the main underground corridors, an annual average of approximately 520 L/s of groundwater, with a varying share of seawater, was pumped from the mines to enable coal

exploitation. In the period before the final abandonment, due to the closure of several levels in the Raša and Labin pits, annual average groundwater pumping had decreased to 350 L/s. The final immersion of the mines began in March 1988, and was completed by the overflow of main water from the Labin shaft to the Rabac drainage gallery in May 1991 (which lasted three years and two months). Based on these data and the estimated volume of the flooded space, an average recharge of 102 L/s was calculated. Initial recharge was likely to be equal to pumping immediately before the flooding, i.e., approximately 350 L/s. Later, with the water table rise and by the reduction of the hydraulic gradients, the recharge decreased and was considerably less than the calculated average of 102 L/s.

During flooding, the mining areas were primarily filled with fresh groundwater, but they were also partly filled with seawater. Since the coal mines are situated in a coastal karst area, with some parts of the mines being less than 1 km from the coastline, and with the exploitation taking place far below sea level, the salt water intrusions were expected. When considering the possibility of using mining waters, it is particularly important to discuss the seawater penetration mechanism and the expected variations in the future. In this respect, it should be noted that the highest seawater recharge was at the initial stage of flooding, and it has decreased with the reduction of the hydraulic gradient. The total amount of seawater intrusion cannot be quantified.

After the mines were flooded, the balance between fresh and seawater was established. The balance is partly defined by natural conditions but, at the same time, significantly affected by the fact that the maximum groundwater levels are limited due to the positioning of the artificially formed drains, i.e., by discharge through the Rabac and Cerovo drainage galleries.

Although some deviations in anisotropic karst environments have been observed, variations in chloride concentrations in mining waters can be generally interpreted according to the well-known Gyben-Herzberg relationship. At low water conditions, the groundwater level in the Labin shaft drops to approximately 6 masl, which means that the expected depth of the sea and freshwater interface should be approximately –240 m. Under such conditions, deeper parts of the mine are exposed to the seawater intrusion. Since the groundwater state is low to moderate for most of the year, significant amounts of seawater are able to intrude deep into the mainland. Due to the possibility of draining through the Rabac and Cerovo galleries, the maximum groundwater levels are limited during the high-water conditions. As mentioned, the highest recorded levels in the Labin shaft reached approximately 13 masl (Rubinić et al., 1995). In such conditions, the interface zone should be depressed at a depth of approximately –420 m; i.e., only the deepest parts of the mines (Ripenda pit) are exposed to the intrusion of seawater. Given the karst characteristics of the aquifers, the groundwater level rise following precipitation events is very fast. Because of this outcome, there is not enough time for the gradual extrusion of the salty water, which enters the system during longer low water periods. The trapped part of the seawater rises up to the natural

cavities and mining corridors above the interface zone and ultimately drains through the Labin shaft and the Rabac drainage gallery.

The studies noted that the highest concentrations of chloride are present in the initial phase of overflow. With sustained high water conditions, the chloride content stabilizes and then gradually decreases. When such conditions cease, the chloride content gradually decreases, and in the upper part of the aquifer, a lens of completely fresh water is formed. It is interesting to note that even after the long dry period recorded in 2003 (Figure 3), its depth did not exceed 60–70 m. It is evident that the anthropogenic changes in the aquifer have had a significant effect on the processes of mixing fresh and seawater, and have caused significant deviation from the Gyben-Herzberg relation. This finding is also confirmed by the sudden changes in the physico-chemical characteristics of the groundwater in the area of the particular mining horizons (Figure 5).

Conclusion

Despite the favourable hydrogeological conditions, and with the remarkable drainage potential of more than 76 km of the mining works, the established hydrochemical characteristics of mine water have been shown to be a limiting factor for their use. One of the highlighted problems is the excessive chloride content due to seawater intrusions. It is significant that with changes in the dynamic conditions of the aquifer, the high chloride content rises from the deeper parts of the system and spills over into the overflow water. It can be assumed that a similar process would occur in the case of dynamic changes induced by water pumping. Because of this assumption, the mine water is not rated as a potential source of potable groundwater. It should be mentioned that in addition to chlorides, excessive levels of other minerals such as iron, manganese, and sulphate were measured in deeper parts, and further limit the utilization of groundwater from the abandoned Labin coal mines.

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